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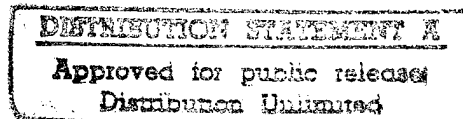
Sir:

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**LIQUEFIED METAL JET PROGRAM  
AUTOMATION AND ROBOTICS  
RESEARCH INSTITUTE (ARRI)**

**FINAL TECHNICAL REPORT**

**Sponsored by:**  
**Advanced Research Projects Agency**  
**(ARPA)**  
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**Liquefied Metal Jet Program (LMJP)**

**ARPA Order No. 9328/03**

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**15 December, 1995**



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## ACRONYMS

BMP	Best Manufacturing Practices
CAD	Computer Aided Design
DoD	Department of Defense
JIT	Just-in-Time
LMJ	Liquid Metal Jetting
PWB	Printing Wiring Board
RCC	Remote Center Compliancy
SNL	Sandia National Laboratories
TI	Texas Instruments
TZM	Tungsten-Zirconium-Molybdenum
UTA/ARRI	Automation & Robotics Research Institute of the University of Texas at Arlington
VOF	Volume of Fluid
WL/MTE	Wright Laboratory

# **LIQUEFIED METAL JET PROGRAM AUTOMATION AND ROBOTICS RESEARCH INSTITUTE FINAL REPORT**

## **1.0 ABSTRACT**

Department of Defense (DoD) agencies are major users of electronics and are responsible for much of the current printing wiring board (PWB) manufacturing. Current manufacturing of PWBs utilizes photolithography and chemical etchings which are subtractive processing techniques creating tons of hazardous waste materials and waste water each year. The current processing techniques apply photoresist to the surface of a copper clad board only to remove more than 90 percent of both copper and resist in the next phase of processing. The subtractive process is, by design, a wasteful processing technique. Current manufacturing processes limit the line size and spaces which determine the circuit density and number of PWB layers.

The proposed alternative manufacturing technology is Liquid Metal Jetting (LMJ). While offering significant reductions in hazardous waste produced and reduced overall processing cost, LMJ can also excel in one-of-a-kind and replication type PWB board production. The proposed process can produce extremely fine PWB patterns with circuit lines much smaller than existing technologies. With a direct Computer Aided Design (CAD) interface, the LMJ process is especially compatible with one-of-a-kind and rapid prototyping applications. This just-in-time (JIT) fabrication and replication fits directly into such DoD agency missions as the deployment of facilities to support the line of battle.

This two-year study was a teaming effort among Texas Instruments (TI) and the Automation & Robotics Research Institute of the University of Texas at Arlington (UTA/ARRI). Other participants included Sandia National Laboratories (SNL), Wright Laboratory (WL/MTE), and the Best Manufacturing Practices (BMP) program from the Office of the Assistant Secretary of the Navy (Research, Development and Acquisition). This study created a demonstrable prototype system capable of manufacturing PWBs via an additive process. The project was based on UTA/ARRI's current Solder Jet research program which has developed a proprietary system capable of printing very precise droplets of lead-based solder for electronic soldering applications.

## **2.0 EXECUTIVE SUMMARY**

The LMJ project has demonstrated the feasibility of using LMJ technology in PWB manufacturing. Significant cost savings, reduced cycle times, and reduced environmental wastes



would be realized with the industrialized use of this technology. Although LMJ PWB manufacturing will probably never replace large volume manufacturing methods, its direct CAD input one-of-a-kind capability has value for mid to small volume production and engineering prototyping.

As a direct result of this ARPA sponsored research project, many significant research issues were resolved and several technological breakthroughs were realized. The ARRI research effort has expanded the science and practice of LMJ technology to include much higher temperature jetting and higher printing speeds (due to continuous jetting).

Significant accomplishments include:

- Highest speed stable jet with controlled breakup (up to 100 KHz)
- Highest temperature droplet generator
- Unique high temperature and high pressure nozzle designs (2300°F)
- Advanced metallurgical research
- Advanced filtering methods
- Advanced ceramic insulator and construction materials for copper jetting
- Resolved intermetallic issues on solder/tin jetting
- Produced coupons demonstrating the use of solder as a resist.

Remaining technical issues include:

- Resolve intermetallic issues on copper system
- Complete fabrication and testing of copper print capability for the existing copper droplet generation system
- Develop high precision and high speed x/y table capable of using the enhanced speed of continuous jetting
- Develop 3D printing capability to identify futuristic interconnect technologies.

On November 27, 1995 the ARRI LMJ laboratory successfully perturbed a jet of molten copper and dispensed molten copper balls. Although the jet only remained stable for a brief period of time, the researchers were able to determine that the high temperature actuator operated in the 2300°F environment.

### **3.0 BACKGROUND**

#### **3.1 Problem Statement**

For today's electronics manufacturers and design engineers the demand for components and circuitry with improved speed, compact design and consistent reliability is clear. Criteria such as

faster clock speeds, increased power dissipation, higher frequencies and greater I/O counts require maximizing the use of real estate on a substrate and minimizing package sizes. These demands are fueling the need for improvements in wire bonding, especially fine pitch technology, reductions in chip-to-chip spacing, and shortening wire bond lengths among other issues.[1] In addition to these challenges, increases in the cost of meeting line width/pitch requirements must be addressed by the original equipment manufacturers (OEMs).[2]

Since 1989 the commercial value of PWBs has exceeded \$5.3 billion (U.S.) annually. Existing technologies utilized in this extensive manufacturing and assembly of PWBs have not fundamentally changed over the past forty years. PWB production still remains, for the most part, a plating and subsequent chemical removal process. Likewise, plating of multilayer vias, through holes, and surface mount of components of PWBs, continues to be based on the application of lead-based solders and various fixing compounds. These methods generate millions of pounds of copper, copper contaminated lead, and lead contaminated waste compounds every year. In addition, the flux and photolithographic chemical clean-up associated with the manufacture of PWBs generates on the order of 6 billion gallons of waste water per year. Almost all of the flux and photolithography chemicals and approximately 80 percent of the copper is passed through the process as waste. This waste and inefficient material utilization with the attendant impact on environment and national productivity cannot be overcome without a major modification in the current technologies of PWB manufacturing.

The continuous pressure toward miniaturization in most electronics manufacturing over the past four decades also is evident in PWB production. Methods of PWB manufacturing currently in use appear to be reaching a limit of diminishing returns in terms of smaller sizes with attendant increase in packaging densities. Issues which were of no consequence at larger sizes have now become the determining factors in the manufacture of PWBs. The general state-of-the-art for PWBs is about 24-mil pitch (i.e., 12-mil metal line with 12-mil space) with some special DoD requirements achieving 10-mil pitch. At these finer pitches a reduction of effort and cost does not presently appear feasible using current technology.

### **3.2 Solution**

Solutions to these problems are under investigation throughout the world. A careful analysis of competing technologies was performed by UTA/ARRI. Although many of the identified

technologies could resolve some concerns, ink jet technology was recognized as a novel solution which could address cost, performance, and ecological concerns. This study addresses remediation for both of the proceeding technical problems by the introduction of LMJ technology in an adaptation of current ink printing methods. This novel technology is an adaptive process which will eliminate all photolithographic waste and most of the chemical removal waste, while having potential for producing even submicron line widths which would be a reduction, by a factor of a 100, in size. A further intrinsic advantage of the LMJ is the ability to produce PWBs JIT and in variable mix PWB batches down to one board at a time.

The development of LMJ as an environmentally compatible process for PWB manufacturing and assembly is at the forefront of research concerns at the UTA/ARRI. UTA/ARRI's Solder Jet research team has developed a printing technology for the extremely precise application of lead-based solder. This technology is based on an adaptation of the industrial standard ink jet printing process. Existing support from the State of Texas, TI, Motorola, IBM, and Tandy has allowed UTA/ARRI to develop a major research program in this area. The Liquid Metal Jet systems under development at UTA/ARRI are capable of dispensing molten metal droplets, (liquid copper and non-leaded-based solder), in the size range of 80  $\mu\text{m}$  to 200  $\mu\text{m}$  in diameter at temperatures in excess of 2300°F.

The approach selected in the LMJ study includes the use of the UTA/ARRI proprietary print head design. Unlike existing ink jet print heads which use piezo crystals to induce the capillary wave onto the issuing jet, the UTA/ARRI head uses proprietary technologies for the jet excitation. This approach removes the piezo-based temperature barrier allowing the extension of ink jet printing technology into the areas of higher melting temperatures metals such as copper.

A major challenge for manufacturers is to reduce environmental concerns by minimizing the production of waste and hazardous materials. Unfortunately, many current processes such as etching and photolithic processes for PWB circuits are not environmentally sound. One method to accomplish this is through the use of additive processes which produce little or no waste. Finally, manufacturers must significantly reduce cycle time by using "batch of one" JIT techniques and rapid prototyping.

#### **4.0 BACKGROUND OF JETTING**

The jetting of liquids has been studied for over 200 years. The Frenchman Nollet wrote in 1754 of observations made on a low-speed stream issuing from a small diameter nozzle [6] using PZT crystals.[31, 32]

#### **5.0 LIQUID METAL SYSTEM FOR PWB MANUFACTURING**

This research group has studied the use of LMJ technology for PWB manufacturing processes. The goal of the ARPA project was to prototype a system for PWB manufacturing that will dispense individually controlled, higher temperature melting point metal droplets. Several LMJ prototype systems were used to investigate the dispensing of various materials directly onto substrates - thus creating an alternative additive process for PWB manufacturing.

The designed system is a high-speed, continuous metal jet system which was chosen for its ability to dispense the large number of droplets per second (10,000-90,000 KHz) needed for PWB manufacturing. This dispensing method is used in other high-speed applications such as printing patterns on checks, aluminum cans, and paper towels. The system is capable of producing individual balls. By controlling placement and the substrate conditions, individual balls can be placed across the substrate to form a line of individual wetted droplets or they can be deposited in a grid array of solder bumps with wetting angles less than 90°. These bumps can then be reflowed later. Three dimensional stacked structures of very large height to width ratios (10:1) and cantilever structures can also be produced.

The system can be divided into five distinct subsystems:

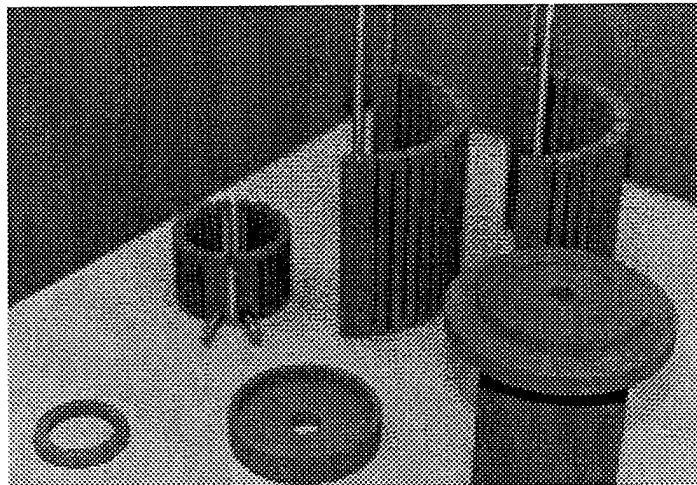
1. Fluidizer
2. Droplet generator
3. Jet/droplet stream
4. Target chamber
5. System control.

##### **5.1 Fluidizer, SOW 5.2.1**

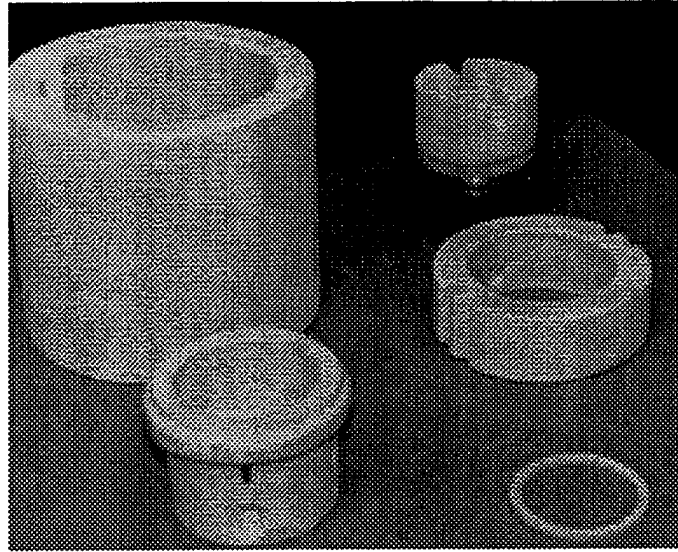
The fluidizer module for the LMJ system converts the solid metal feedstock to liquid. The fluidizer module introduces the metal feedstock at a predetermined rate into a high temperature melt chamber. Propelling forces are required to drive the liquid metal jet at the predetermined velocity. The resulting liquefied metal is transitioned to the droplet generator for subsequent droplet formation.

Major components of the fluidizer design include the melt pot, heating elements, insulation and pressure vessel as shown Figures 1, 2, and 3. An open top, cylindrical carbon-graphite melt pot (350 cc capacity) is designed to contain and filter the Cu load. Tapered regions (ID and OD) on the pot mate with a carbon-graphite tapered (ID) disc and a TZM tapered (OD) tube to form dynamic "needle and seat" style seals through pressurization (maximum 500 psi @ 2500°F) of the fluidizer/droplet generator assembly. Carbon-graphite elements surrounding the pot utilize resistance heating (7 KW) to melt the load. Machinable ceramic insulation materials consisting of low density silica foam and high density fibrous refractory sheet form a thermal boundary for the heated zone. The pressure vessel, Figure 4, was constructed from 4140 steel, and provides structural containment for the insulation, heating elements, and melt pot. Access for top loading and servicing of the melt pot and droplet generator as an assembly has been designed into the vessel as seen in Figure 3. Additionally, the vessel's baseplate is temperature controlled, through an embedded counter-flow heat exchanger, which allows it to serve as a structural barrier between the fluidizer and droplet generator heated zones.

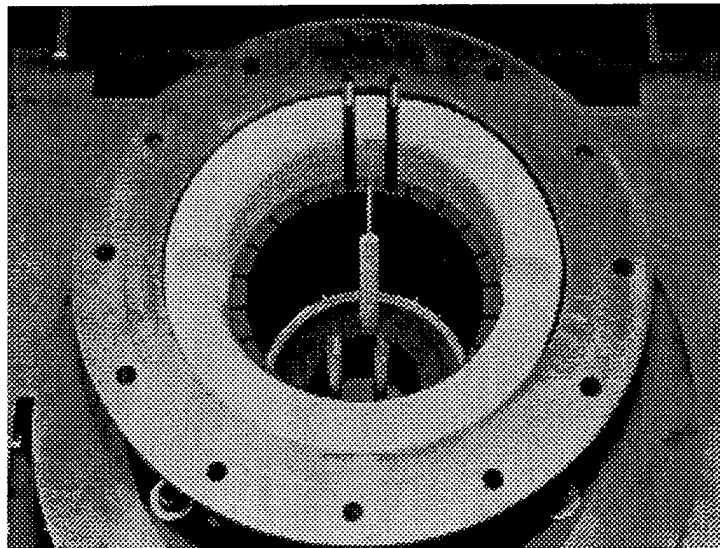
- The non-lead fluidizer design continues to operate to specification and performs satisfactorily.
- The copper fluidizer is complete and is operational.



**Figure 1. Carbon Graphite Components**



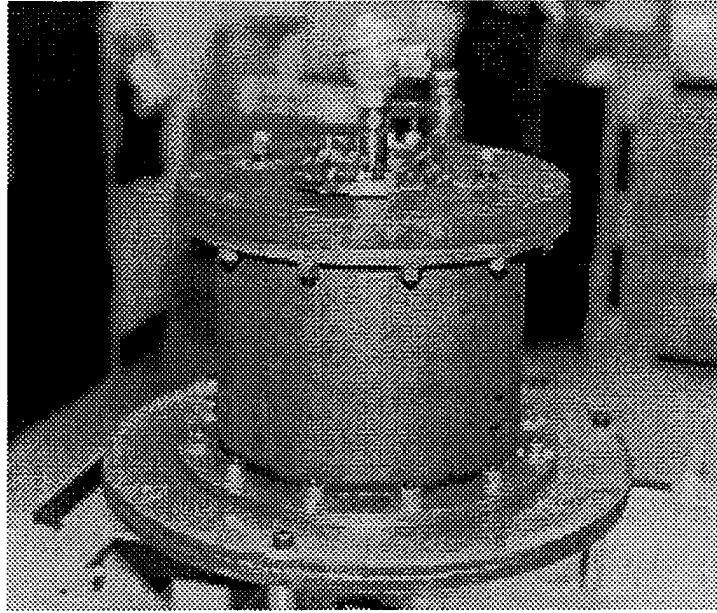
**Figure 2. Ceramic Components**



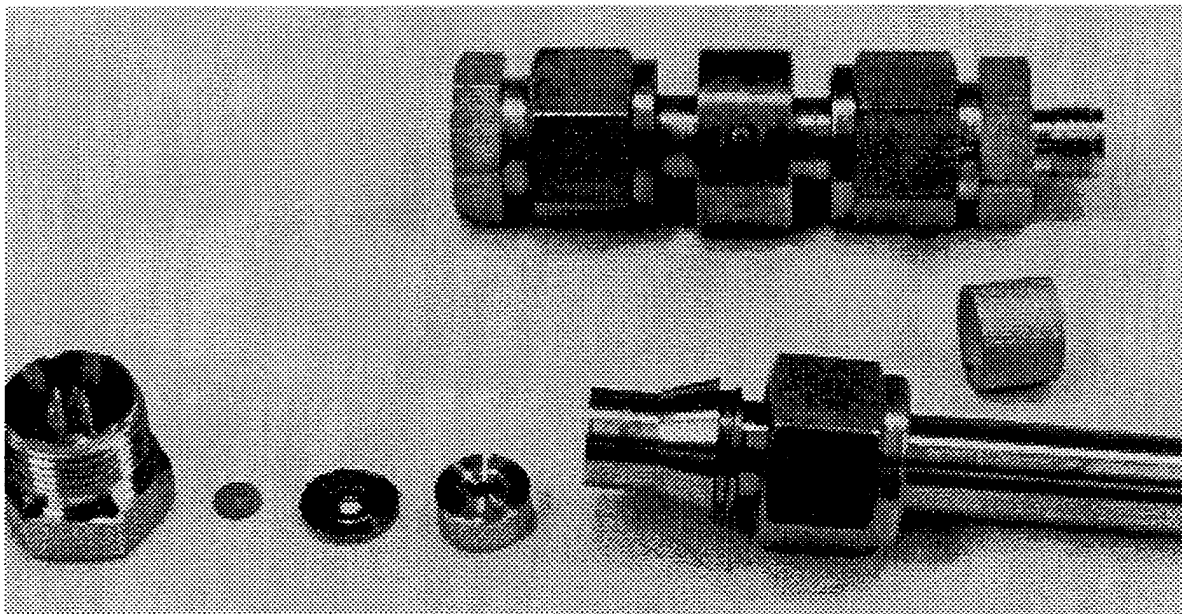
**Figure 3. Top View of Copper Pressure Vessel**

## **5.2 Droplet Generator, SOW 5.2.2**

The proprietary droplet generator for the LMJ system accepts the liquefied metal from the fluidizer and controls the instability required to excite the jet stream into a repeatable droplet formation. The non-lead droplet generator is shown in Figure 5. In the non-lead solder dispensing system, the droplets have a charge induced by an induction plate as they break away from the jet. A signal level is provided to charge the solder droplets so the trajectory through an electric field



**Figure 4. Copper System Pressure Vessel**



**Figure 5. Non-Lead Solder Nozzle Assembly**

can be controlled. After being charged, the solder droplets will continue through an electrostatic deflection field, to impact the target at a precise location.

Major components of the droplet generator design include the transfer tube, actuator, orifice, charging mechanism, heating element, and insulation/structural support. A TZM tube transfers pressurized liquid Cu to a sapphire orifice and provides mechanical coupling between the fluid and

molybdenum actuator. The carbon-graphite heating elements shown in Figures 1 and 3, utilize resistance heating (3 KW) to maintain the Cu in a liquid state. The low density silica foam and the heated zone and provide structural support. In addition, a nitrogen purge is used to protect the materials in the heated zone from oxidation effects due to the extreme temperature catalyst

- The non-lead solder droplet generator continues to operate to specification and performs satisfactorily.
- The copper droplet generator has had marginal success in generating droplets. Significant problems were found in the vessel seals as well as nozzle plugging issues.

### **5.3 Jet/Droplet Stream, SOW 5.2.3**

A path for the droplets to be charged and deflected is provided in the design of the non-lead solder system. The path also provides for alternative atmospheres for experimentation.

Major components of the jet/droplet stream design include the deflection mechanism, thermal management, nitrogen entrainment, and stream alignment. The deflection mechanism consists of two slide-mounted, high voltage (relative to the charger) carbon-graphite plates and carbon graphite heating elements, utilizing resistance heating (5 KW), mounted in a modular ceramic shell to contain the primary environment. Features include observation ports above and below the deflection plates which can be slide retracted during initial stream alignment and nitrogen entrainment for stream and material protection from oxygen. The fluidizer/droplet generator assembly is mounted to a Remote Center Compliancy (RCC) adjustment mechanism which serves to align the liquid copper jet stream (at the orifice) parallel with the deflection plates and normal to the target surface using translation ( $x,y$ ) and angular ( $\theta,\phi$ ) modes.

- The environmental chambers for both systems are fully operation and performing as expected.

### **5.4 Target Chamber, SOW 5.2.4**

The test coupons (i.e., samples) on which the experiment is run, reside in a fixture to hold the coupon and a chamber to provide for controlled inert atmosphere. This chamber provides controlled heat for coupon preheating, and provides for optical observation and instrumentation. In addition to the chamber, a precision motion control system to position the coupon for pattern writing has been designed, acquired, and integrated into the non-lead solder LMJ system. A device to catch and collect the unwanted or "guttered" droplets is included in the non-lead solder



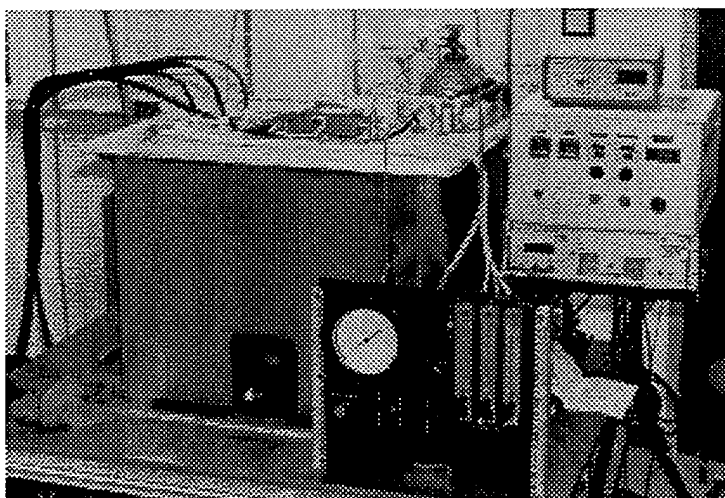
coupon chamber. The target chamber on the copper system is a simple ball catcher to verify the feasibility of copper jetting and was not intended to print patterns.

Major components of the target chamber design include the environment chamber, remote video observation, gutter, target fixturing, and an  $x,y,z$ -table. An outer environment shell contains the secondary nitrogen environment for the whole process and accommodates visual process observation/verification. Special attention is given to the design of a structure that allows frequent servicing of inner systems while prohibiting direct operator contact during process heat-up, operation, and cool-down. Target fixture temperature is elevated by the close proximity of a heated carbon-graphite gutter mounted beneath the deflection mechanism.

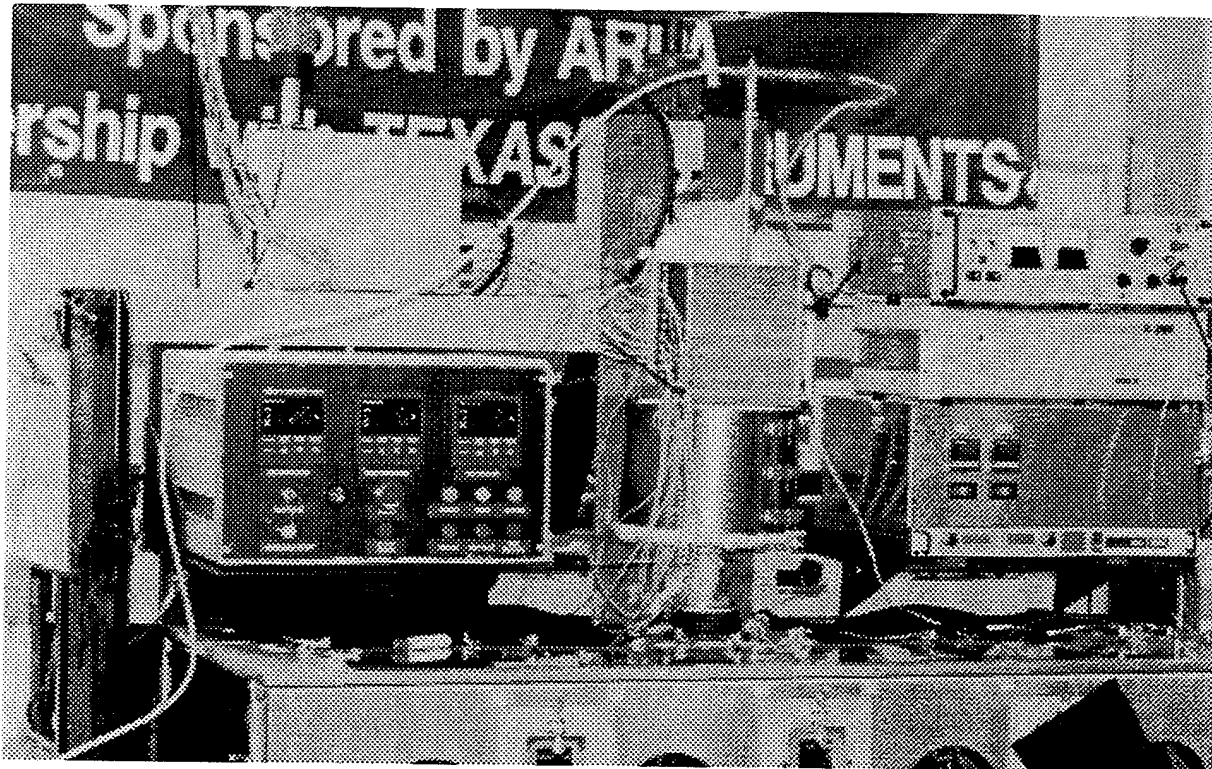
- The non-lead target chamber is complete and fully operational.
- The copper target chamber is complete and fully operational.

#### **5.5 System Control, SOW 5.2.5**

The system controllers shown in Figures 6 and 7, address all items necessary to control and monitor the process. Subtasks included hardware, software, and integration for process control, environmental control, data acquisition, and safety. The system control includes personal computers, programmable logic controller, data acquisition software, CAD data, Network Control program interface, and custom programming. Facility related subtasks included, fume handling capabilities, safety systems, and thermal management equipment.



**Figure 6. Copper System Environment Chamber and Control System**



**Figure 7. Non-Lead System Environment Chamber and Control System**

Major components of the system control design address process pressure, independent zone temperature, environment gas, and safety systems. Open-loop control is used for fluidizer/droplet generator assembly pressurization, environment gas content level management, and baseplate cooling. Independent closed-loop temperature control is used for fluidizer, droplet generator, and jet/droplet stream zones. Temperature sensing in all extreme heated zones is accomplished through the use of type S thermocouples. In the event of an E-stop condition or catastrophic failure, safety systems are included to safely vent hot process gases through heat exchangers and contain a liquid metal spill while protecting operation personnel and the more costly systems.

- The system control computer for the non-lead is complete and operating within specifications.
- The system controls for the copper system is complete and operational within design specifications.

## **6.0 RESEARCH FINDINGS**

Many technical issues were resolved during the course of this research program. These include:

- Highest speed stable jet with controlled breakup (up to 100 KHz)

- Highest temperature droplet generator
- Unique high temperature and high pressure nozzle designs (2300°F)
- Advanced metallurgical research
- Advanced filtering methods
- Advanced ceramic insulator and construction materials for copper jetting
- Resolved intermetallic issues on solder/tin jetting
- Produced coupons demonstrating the use of solder as a resist.

Remaining technical issues include:

- Resolve intermetallic issues on copper system
- Complete fabrication and testing of copper print capability for the existing copper droplet generation system
- Develop high precision and high speed x/y table capable of using the enhanced speed of continuous jetting
- Develop 3D printing capability to identify futuristic interconnect technologies.

Due to the elevated temperatures of molten copper and tin, significant research was necessary to identify and evaluate compatible materials. Prior to beginning of the actual subsystems design, four major areas required considerable research. These areas, identified through design parameter and process variable specifications, include construction materials, heating methods, heat zone sealing/joining, and environment effects. In addition, vendor searches were performed whenever applicable to determine the cost effectiveness of designing and constructing systems versus purchasing off the shelf technology.

In the tin system, corrosion and intermetallic formations were the main issues to be researched. 316 Stainless Steel materials were used for most of the research vehicle. Intermittent plugging of nozzles and subsequent deterioration of fluidizer material indicated that a better suited material will be necessary for any long term research or production system. Some attempts were made to use ceramics and ceramic liners to alleviate the problem. Although the ceramics have superior corrosion resistance, thermal stress due to temperature cycling severely damaged the ceramic components and added further complications to the plugging issues. The pursuit of using better ceramics and installing tighter temperature control was cost and schedule prohibitive, but will probably solve many issues in a production environment.

As expected, the copper system proved to be an even more complex problem. The temperature and reactivity of molten copper required the use of some rather exotic metals as well

as expensive ceramics. Materials research included refractory elements, ceramics and carbon-graphite's as well as high temperature super alloys of steel, titanium, cobalt, and nickel. High temperature static, dynamic (flowing Cu) and electrical tests and evaluations were performed on favorable candidate materials. A molybdenum alloy and amorphous carbon-graphite were found to be the most suitable materials for construction of parts either in direct contact with the liquid Cu or within the heated zones. An extensive materials research effort was performed by the ARRI engineering staff and a summary of the data is shown in Tables 1 and 2.

**TABLE 1. BASELINE MATERIAL DESIGN CRITERIA**

Operating Temperature Range	2200 - 2500°F: Cu melting point 1984°F
Operating Pressure Range	200 - 500 psi yield stress, ductility, creep stress
Chemically Inert to Cu	Not susceptible to liquid metal embrittlement by Cu
Oxidation Resistance	Air Inert gas (nitrogen) environments
Machinability/Weldability/ Processing History	Ease of machining Tendency to gall or seize
Availability/Cost	Tubing, plate, round, and bar stock

**TABLE 2. CANDIDATE MATERIALS EVALUATED**

400 Series Stainless Steels	Resist oxidation Inadequate strength
Titanium and Ti Alloys	Service temps <800°F Intermetallics formed with Cu
Nickel and Cobalt Super Alloys	Strength adequate React with copper
Refractory Metals (Molybdenum, Tantalum)	Strength adequate Oxidation resistance inadequate
Graphite	Lower strength than refractories Could be used in heating
Ceramics	Strength, thermal shock, machinability, interface with other materials

Sources of heating that were investigated include resistance, induction, and IR methods. While induction heating was determined to be a more efficient method, resistance heating was chosen as being sufficient for the needs of this research vehicle based on cost comparisons. Heat zone sealing/joining techniques research concentrated primarily on current methods utilized in both the pressurized and continuous casting industries.

Using the environmental chamber shown in Figures 6 and 7, we identified the effects of extreme temperature on materials in the presence of inert gases and any hazardous molecular phases that might be formed. Nitrogen was chosen as both the process gas to propel the liquid Cu

stream and environment gas to protect the in flight stream and construction materials from the effect of oxygen at the extreme temperatures.

Zirconium phosphate ceramic was determined to be an ideal structural material for thermal management based on its high strength, high thermal shock resistance, and low thermal conductivity. However, construction costs and delivery estimates were prohibitive. As a result, system heat and cool-down times were increased to utilize machinable classes of ceramic materials that include low density silica foam, alumina, and high density fibrous refractory sheet.

Based on this research effort and available vendor information, the metal of choice was a Tungsten-Zirconium-Molybdenum (TZM) alloy. Preliminary testing indicated that no reactivity between copper and the TZM was found. Additional data provided by the manufacturer supported this choice of material. Tables 3 and 4 show the material characteristics of TZM.

**TABLE 3. MOLYBDENUM (MO) CHARACTERISTICS**

Melting point 4750°F, density 0.369 LB/in, bcc crystal structure
Yield Strength 40 ksi, Creep Stress (0.5% elong./100 hr @ 2200°F) 11 ksi
Chemically inert to Cu @ 2200°F, some diffusion after 200 hr @ 3000°F
Rapid oxidation above 1400°F (oxide melting point 1460°F)
No reactivity with nitrogen
Machined with hss or carbide, TIG welded in argon or helium atmosphere
Available in all forms (sheet, tubing, round or bar stock) "Climax Metals"
\$50.00/LB, \$3.50/in standard 1/4" tubing, \$4.50/in 1/2" dia. round stock
Dies, turbine parts, heat pipes, pressure vessels, furnace parts, bearings

**TABLE 4. PREFERRED MATERIALS FOR COPPER SYSTEM**

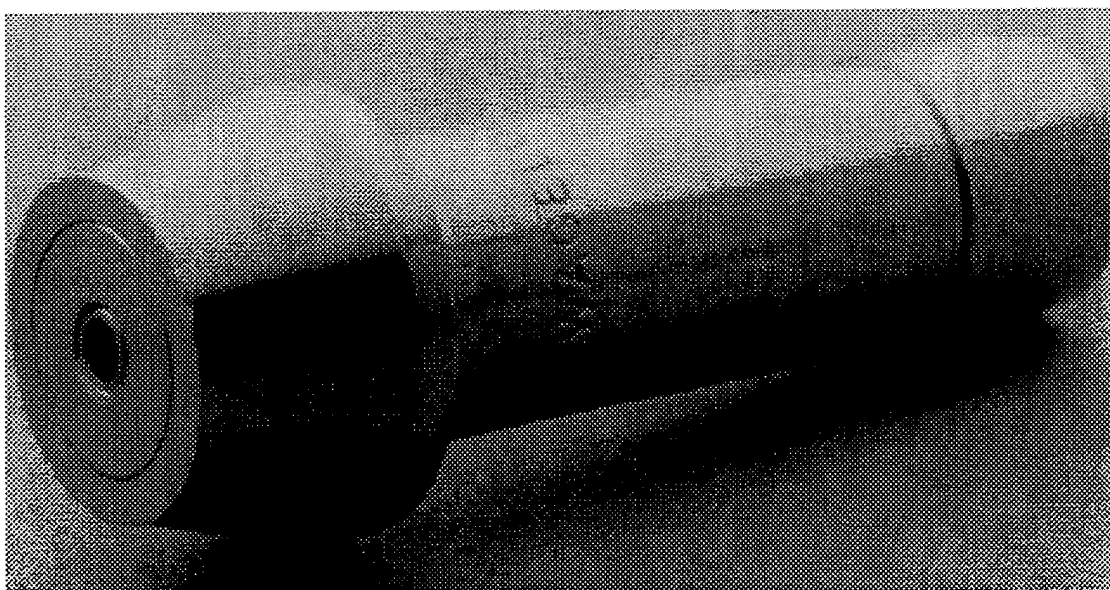
Molybdenum (Mo) and TZM alloy (all properties are @ 2200°F)	Head assembly, actuator, charge ring and orifice mounting
Carbon graphite with SiC conversion (all properties are @ 2200°F)	Heater elements, containment vessel, liquid seals, deflection plates, and gutter
Zirconium phosphate ceramics	Thermal insulators and thermal barriers
316 stainless steel	Pressure vessel construction and structural support (outside thermal zones) readily available in all forms (various distributors)
Grafoil gaskets	Pressure seals at temperature

Due to the expense and machining difficulty of TZM, carbon graphite was chosen for the fluidizer vessel. The liquid copper appeared to have reacted with the TZM material used in the nozzle and caused the orifice to plug. Further research was able to find obscure Russian references indicating that there may be some reactivity between copper and Molybdenum under certain conditions which apparently match the conditions in our experiment. In an effort to

complete this research project within the time and budget constraints, a very low pressure system used a transfer tube and nozzle assembly made of carbon graphite. In the final stages of this contract, the materials were tested in the research vessel and proved adequate.

The high-speed printing technology developed on an earlier project continued to work in the high temperature environment required in the LMJ project. Sustained stream control and droplet generation was demonstrated to operate at speeds up to 100 KHz. This same generator was demonstrated to operate under extreme temperatures as seen in the copper system. Due to material selection, the actuators and nozzle assembly could only be used one time. Further research would be required to develop a more suitable production style nozzle assembly.

High temperature and high pressure sealing problems were solved. A great deal of effort and money was expended to resolve the orifice sealing and plugging problems. Several hundred vendor-mounted orifi, as shown in Figure 8, were purchased and tested in the tin system without success. Consequently, the research team decided to design and develop the in-house orifice and holder shown in Figure 5. This system is in use and performs adequately at lower cost. An additional benefit to this design is that it simplifies the cleaning process and allows for inlet and outlet material examination.

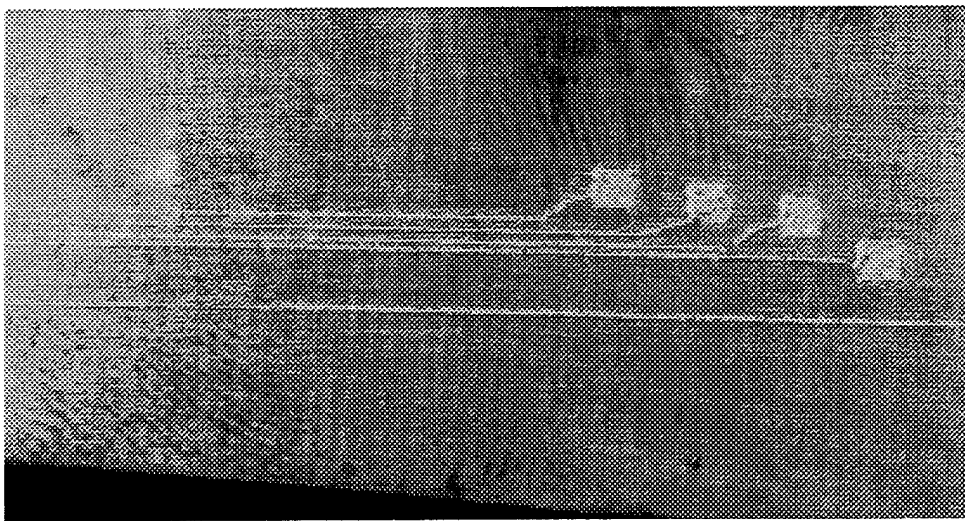


**Figure 8. Vendor-Supplied Orifice Assembly**

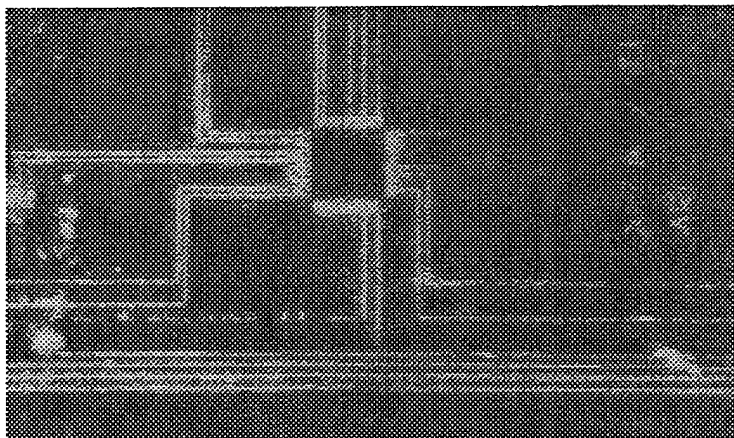
Early in the LMJ project, meetings with material suppliers indicated that liquid metal filtering would not be required since the materials purchased were 99.9999 percent pure (five nines pure),

and, since the metals were extremely dense, the particulates would float to the top of the vessel. This also proved to be misleading. The vendor had no experience with intermetallic particles that are of the same density as the base metal and were solid at the base metal melt temperature. A filtering technology developed in earlier research programs was used to remove insoluble particulates contained in metal feedstock. This solution also was developed in-house as all commercial filtering were either too large, used incompatible materials, or were incapable of operating at the temperatures required.

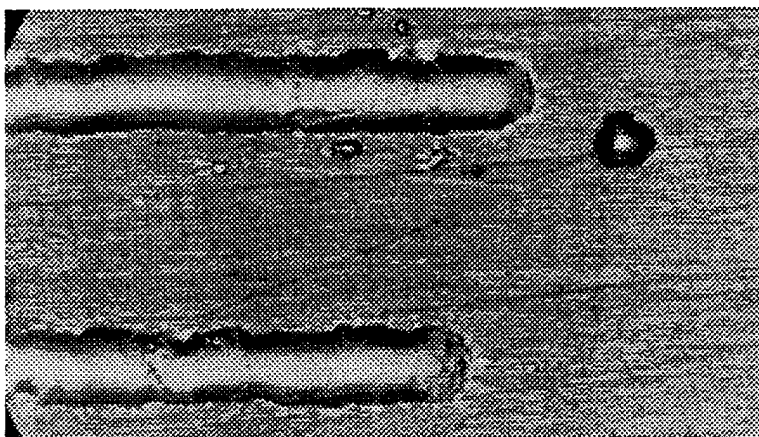
The solder/tin system produced a set of coupons that were etched to demonstrate the use to the solder/tin as an etch resist. As seen in Figures 9 through 12, these coupons show that this technology is viable for use in manufacturing PWBs. The random splatter of solder/tin seen in these figures is from the gutter system overfilling and causing a 'back splash' of solder on the copper substrates. A better design for the charge, deflection and guttering mechanism will be needed for a production system prior to implementation. It is currently being designed under another research contract at ARRI.



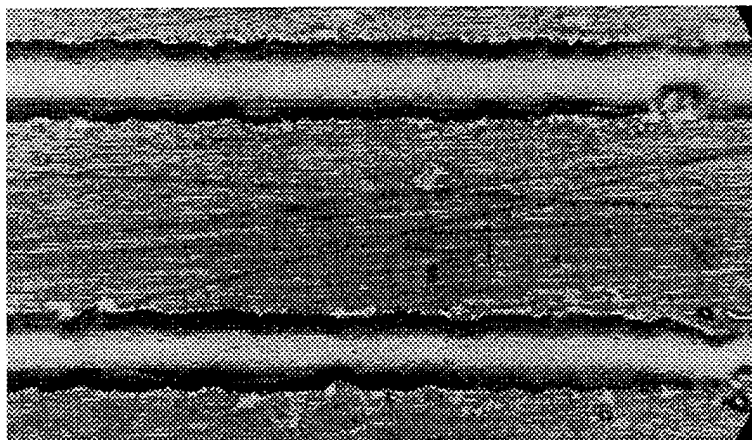
**Figure 9. Printed PWB with LMJ System Prior to Etching**



**Figure 10. Etched PWB Printed with LMJ System**



**Figure 11. Magnification of Solder on Copper Substrate (from Figure 9)**



**Figure 12. Magnification of Solder on Copper Substrate (from Figure 9)**



## 7.0 SYSTEM TEST AND EVALUATION, SOW 5.3

Several system and subsystem tests have been conducted including generating solder coupons and using the solder as an etch resist to generate simple PWBs circuit paths. The non-lead jetting system currently operational in the laboratory has output of 63/37 Sn/Pd solder and pure tin in the form of:

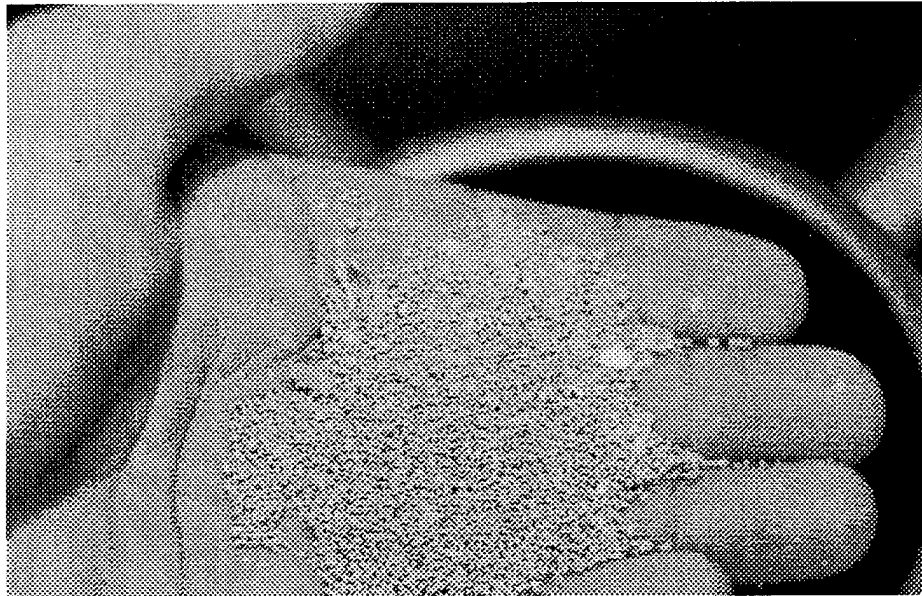
- Printed microballs (80 to 200  $\mu\text{m}$  in diameter)
- Metal spheres (80 to 800  $\mu\text{m}$  in diameter)
- Bumps on copper substrates
- Wetted drops on copper substrates.
- Circuit paths on copper substrates
- Three-dimensional structures.

The copper jetting system currently operational in the laboratory has output pure copper for short periods of time in the form of: microballs (80 to 200  $\mu\text{m}$  in diameter)

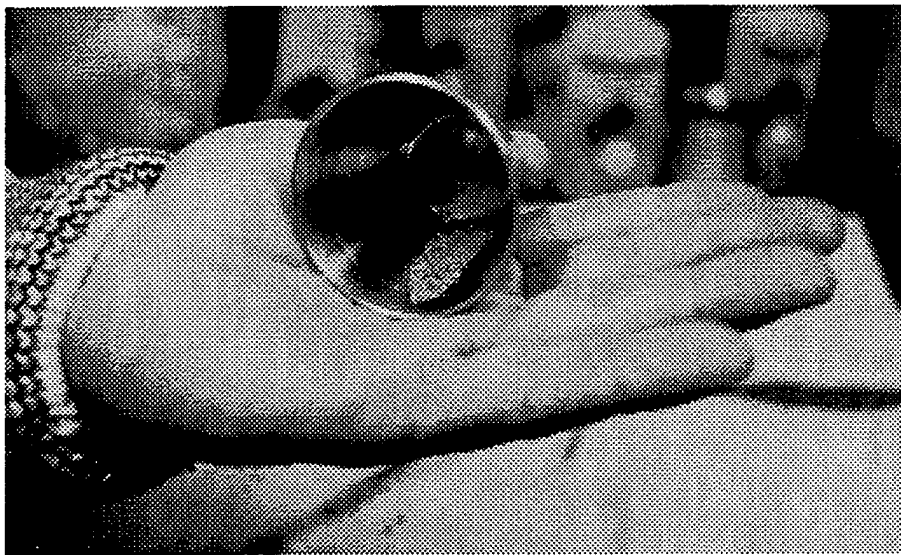
- A complete design for the charge and deflection of the copper droplets was developed, but not fabricated.

Microballs of solder are shown in Figures 13 and 17. These balls were formed by allowing the molten metal droplets to freeze in flight. Some dimples and protrusions are visible on the microball surfaces. Some of irregularities are indicative of perturbations on the surface of the liquid resulting from the surface dynamics of the fluid. The solidification rate of the microballs was rapid enough to freeze in these imperfections. The rapid solidification rate results in a fine microstructure consisting of either the finely spaced two-phase solder microstructure shown in Figure 15 or the equiaxed grain structure shown in Figure 16. The lighter phases of Pb are visible along the grain boundaries of Sn. The potential to formulate joints with a homogeneous, fine microstructure is one advantage of jetting since inhomogeneous and coarsened microstructures are one cause of thermal fatigue failure of conventional SMT solder joints.[33]

As mentioned earlier, the key material parameters affecting jetting are the relationship between surface tension and viscosity. Analyses developed by Smith [17,18] and performed at UTA have indicated that most molten metals can be jetted. Metals that have been jetted include tin, 63/37 solder, low melting point temperature solders, and mercury. Future metal jetting research will include printing with liquid silver, and gold.

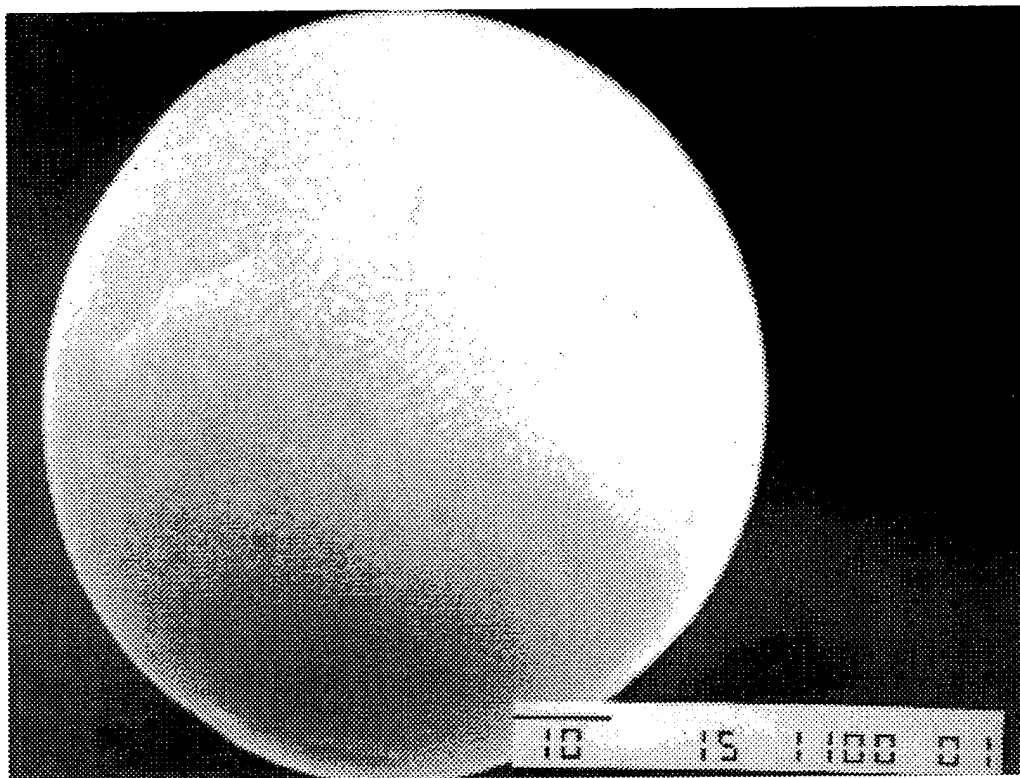


**Figure 13. Non-lead Microballs Generated with LMJ System**

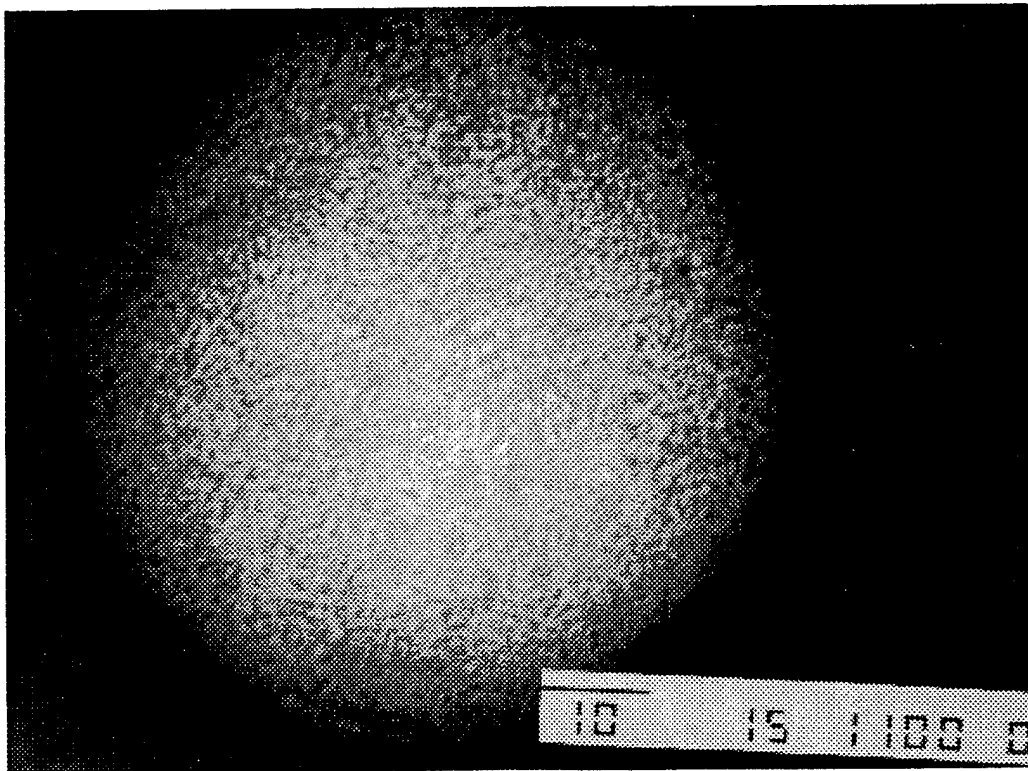


**Figure 14. Copper Microballs Generated with LMJ System**

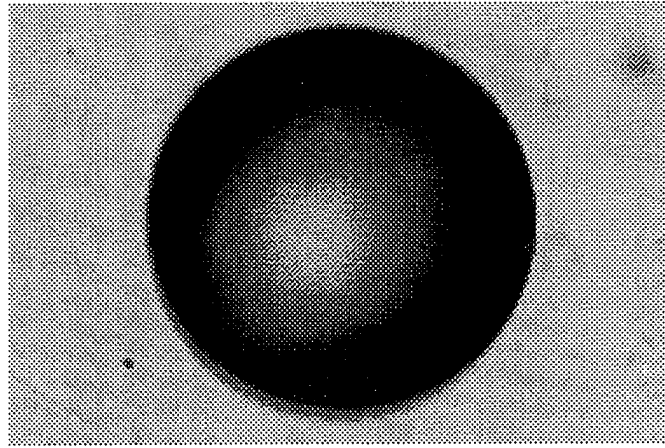
On November 27, 1995 the ARRI LMJ laboratory successfully perturbed a jet of molten copper and dispensed molten copper balls as shown in Figure 14. Although the jet only remained stable for a brief period of time, the researchers were able to determine that the high temperature actuator operated in the 2300°F environment. This event would indicate that it is feasible to jet liquid copper, break it up into a stable stream and subsequently direct the charges balls to a target area. Further research in the application of LMJ in the high temperature ranges will be necessary to commercially adapt this technology for industrial use.



**Figure 15. SEM Photo Showing Finely Spaced Two-Phase Microstructure**



**Figure 16. SEM Photo Showing Equiaxed Grain Structure**



**Figure 17. Copper Microball Generated by LMJ System**

## **8.0 IMPACT ANALYSES**

The impact quality of the droplets must be controlled. Several studies evaluated the impact of liquid metal droplets onto a rigid substrate. There are two numerical methods and one experimental method used to evaluate these numerical methods. The first numerical method, Quasimolecular modeling (Q-modeling), is a first order investigation into the impact. First order means that only the dynamics of the impact is addressed. The second method provides a rigorous investigation using a finite-difference formulation of the Navier-Stokes equation that uses a Volume of Fluid (VOF) algorithm to tract the free surface; this solution algorithm is contained in the code RIPPLE [34] which was developed at Las Alamos National Laboratories.

Theoretical investigations of the impact process assume the following:

1. The study is restricted to drops smaller than 3 mm diameter, making it safe to assume that the initial shape is spherical. [35]
2. The impact is normal to the surface, and since there are no obstructions in the surface to restrict flow, the problem can be assumed axial symmetrical.
3. Since the substrate is thick compared to the droplet size, the substrate-droplet interface temperature can be assumed constant.
4. Since the dominant heat transfer mode is conduction to the substrate, the free surface is assumed insulated.

Results indicate that the impact process is well behaved. The droplets appear to flow evenly over the wetting surface and no satellites are formed as a result of the impact. These are indications that recirculation zones form inside the droplet; thus affecting the solidification process. The important parameters to be varied independently, for a given metal, are the temperature of the liquid droplet, temperature of the substrate, and velocity of the impact.

## 9.0 TECHNICAL ISSUES

Current research shows that a number of technical issues must be resolved prior to metal jetting becoming a successful process in PWB manufacturing. The major technical issues include process stability, material substrate interaction, and circuit performance:

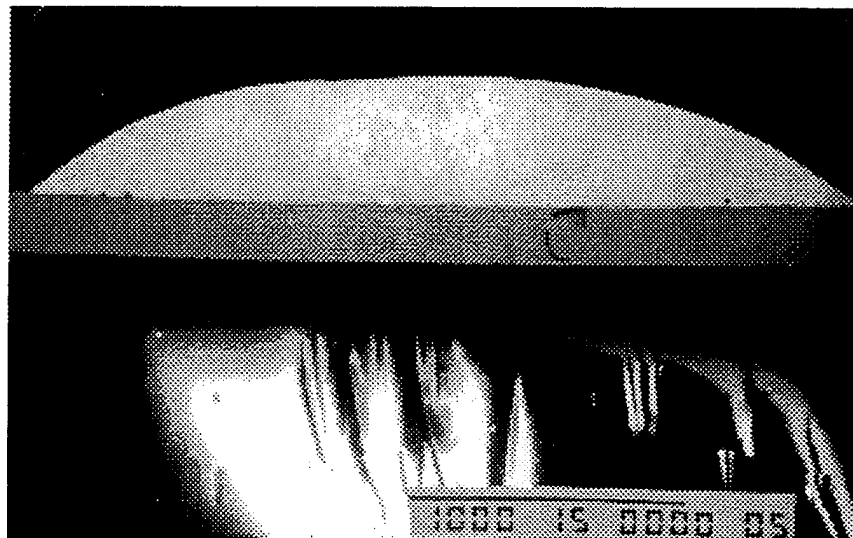
Process stability is a concern due to the complexity of the jetting process. Key challenges include oxidation, material contamination, and thermal management. Empirical evidence shows that a non-oxidizing environment is essential to droplet formation with the jet. It was noted empirically in the lab that a molten tin jet would not break-up into droplets in air. However, the jet would form droplets in an ambient nitrogen atmosphere. Auger electron microscopy of the metal output from both system configurations revealed that the tin jetted in air was heavily oxidized on the surface of the metal relative to the tin jetted in nitrogen. This data indicates that the ability of the jet to break-up into droplets is affected by oxidation of the metal surface and underscores the need for environmental control in jetting.

An important aspect of reliable operation of the jet is eliminating system contamination which can lead to clogging or leaching of contaminants into the molten metals. This means that the choice of both the construction materials used in the design and the filtering methods to remove contaminants in the raw material are important aspects. The presence of particulate matter such as oxides or intermetallic phases can lead to clogging of the jet. For example,  $\text{SiO}_2$  contaminants have been found in the solder even after filtering and ranged in size from approximately 1 to 10  $\mu\text{m}$  in diameter. These particles are large enough to partially or fully block an orifice depending upon the orifice size. Another potential source of system contamination comes from elements of the construction material leaching into the molten metal. This can lead to intermetallic formations such as the In-containing particle which may clog the system, or lead to the introduction of contaminants that may alter the physical and mechanical properties of the deposited materials. Thus, it is important to filter all particulate contaminants from the system and to choose filter and construction materials that will be inert to the molten materials being jetted.

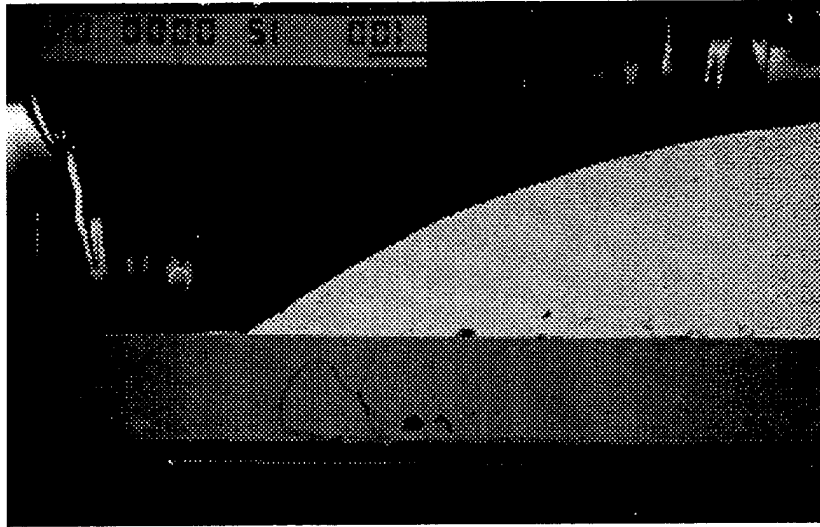
Thermal management is a major challenge for a metal jetting system. High operating temperatures, especially those required for silver and copper, affect system reliability and other important jetting parameters such as viscosity and surface tension. The use of PZT crystals as droplet generators is a major challenge for the higher temperature melting point metals because

the curie temperature of the PZT material may be exceeded. Researchers at UTA have developed alternate high temperatures droplet generators (i.e., non-PZT driven) which have shown high frequency responses to 90,000 drops per second with temperatures over 1100°C.

Control of the jetting process is a function of jet velocity, perturbation wave frequency, orifice diameter, absolute viscosity, surface tension, fluid density, temperature, and substrate parameters such as temperature, surface roughness, etc. The importance of each of these factors to the process and the extent to which these factors interact are questions that must be answered with careful experimentation. Two examples of droplets impacted onto heated copper substrates are shown in Figures 18 and 19. Figure 18 shows a droplet deposited with a high impact speed onto a substrate that was not continuously heated. The resulting droplet has spread well across the substrate but there are outlines of material from the splat that would be unacceptable for a circuit line. Figure 19 shows a droplet deposited onto a continuously heated copper substrate with a lower impact speed. This resulted in good spread with a wetting angle of less than 90° and a well contained droplet shape.



**Figure 18. Impacted Droplets onto Unheated Copper Substrate**



**Figure 19. Impacted Droplets onto Heated Copper Substrate**

## **10.0 SUMMARY**

This project has demonstrated the feasibility of using LMJ technology in PWB manufacturing. Many significant research issues were resolved and many technological breakthroughs were realized. As a result of this research, the science and practice of LMJ technology has been expanded to include much higher temperatures and higher printing speeds (due to continuous jetting).

LMJ technology has far reaching capabilities in the PWB manufacturing industry. Significant cost savings, reduced cycle times, and reduced environmental wastes would be realized with the industrialized use of this technology. Although LMJ PWB manufacturing will probably never replace large volume manufacturing methods, its direct CAD input one-of-a-kind capability certainly has value for mid to small volume production and engineering prototyping.

The use of LMJ technology for fabrication of PWBs will require control of many critical variables. For this technology to become a viable manufacturing process, significant technical issues need to be resolved. These major issues include:

- Resolve intermetallic issues on copper system
- Complete fabrication and testing of copper print capability for the existing copper droplet generation system
- Process parameterization for high temperature metals
- Develop high precision and high speed x/y table capable of using the enhanced speed of continuous jetting.

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